Exotic mesons with hidden charm and bottom near thresholds

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We study heavy hadron spectroscopy near heavy meson thresholds. We employ heavy pseudoscalar meson P and heavy vector meson P* as effective degrees of freedom and consider meson exchange potentials between them. All possible composite states which can be constructed from the P and P* mesons are studied up to the total angular momentum $J \leq 2$. We consider, as exotic states, isosinglet states with exotic J^{PC} quantum numbers and isotriplet states. We solve numerically the Schrödinger equation with channel-couplings for each state. We found $B^{(*)}\overline{B}^{(*)}$ molecule states for $I^G(J^{PC}) = 1^+(1^{+-})$ correspond to the masses of twin resonances $Z_b(10610)$ and $Z_b(10650)$. We predict several possible $B^{(*)}\overline{B}^{(*)}$ bound and/or resonant states in other channels. On the other hand, there are no $D^{(*)}\overline{D}^{(*)}$ bound and/or resonant states whose quantum numbers are exotic.

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1 Introduction

Recently, the exotic twin resonances $Z_b(10610)$ and $Z_b(10650)$ are discovered in the processes $\Upsilon(5S) \rightarrow \pi\pi\Upsilon(nS)(n = 1, 2, 3)$ and $\Upsilon(5S) \rightarrow \pi\pi h_b(kP)(k = 1, 2)$ by Belle group [1, 2]. The reported masses and widths of the two resonances are $M(Z_b(10610)) = 10607.2\pm2.0\,\mathrm{MeV}$, $\Gamma(Z_b(10610)) = 18.4\pm2.4\,\mathrm{MeV}$ and $M(Z_b(10650)) = 10652.2\pm1.5\,\mathrm{MeV}$, $\Gamma(Z_b(10650)) = (11.5\pm2.2)\,\mathrm{MeV}$. These resonances have some interesting properties. First of all, Z_b's have exotic quantum numbers $I^G(J^P) = 1^+(1^+)$. Since Z_b's are isotriplet states, they need four quarks as minimal constituents. So Z_b's are "genuinely" exotic states. Secondly, Z_b's have exotic decay ratios. In general, a decay process with h_b should be suppressed in heavy quark mass limit, because these processes require a heavy quark spin flip. Nevertheless, the decay rates of $\Upsilon(5S) \rightarrow Z_b\pi \rightarrow \pi\pi\Upsilon(nS)$ are comparable to those of $\Upsilon(5S) \rightarrow Z_b\pi \rightarrow \pi\pi h_b$. Thirdly, Z_b's are "exotic twin" resonances. Their mass splitting is only 45 MeV ($\Delta m_{Z_b} \sim 45\,\mathrm{MeV}$). This scale is not typically found in usual quarkonium. These facts strongly suggest that Z_b's have a molecular type structures as noted in Ref. [3, 4]

We can naively expect the existence of molecular states in heavy quark sectors. We have two reasons. One is that the kinetic term of Hamiltonian is suppressed. Because the reduced mass is larger in heavy mesons. Second is that P and P* are degenerate thanks to heavy quark symmetry because the interaction of heavy quark spin is suppressed in heavy quark sector. This leads the effects of channel-couplings become larger.

In this paper we study $\mathrm{P}^{(*)}\overline{\mathrm{P}}^{(*)}$ molecular states in terms of the potential model. We completely take into account the degeneracy of P and P* due to the heavy quark symmetry, and fully consider channel couplings of $\mathrm{P}^{(*)}$ and $\overline{\mathrm{P}}^{(*)}$. And we consider not only bound states but also resonant states.

This paper is organized as follows. In Sec. 2, we introduce (i) the π exchange potential and (ii) the $\pi\rho\omega$ potential between $\mathrm{P}^{(*)}$ and $\overline{\mathrm{P}}^{(*)}$ mesons. To obtain the potentials, we respect the heavy quark symmetry for the $\mathrm{P}^{(*)}\mathrm{P}^{(*)}\pi$, $\mathrm{P}^{(*)}\mathrm{P}^{(*)}\rho$ and $\mathrm{P}^{(*)}\mathrm{P}^{(*)}\omega$ vertices. We classify all the possible states composed by a pair of $P^{(*)}$ and $\overline{P}^{(*)}$ mesons with exotic quantum numbers $I^G(J^{PC})$. In Sec. 3, we solve numerically the Schrödinger equations with channel-couplings and discuss the bound and/or resonant states of the $B^{(*)}\overline{B}^{(*)}$ and $D^{(*)}\overline{D}^{(*)}$ systems. In Sec. 4 is devoted to summary.

2   Method

We employ the effective Lagrangians based on heavy quark and chiral symmetries. They give the interaction Lagrangians of $\pi P P^*$ and $\pi P^* P^*$ with

$$\mathcal{L}_{\pi P P^*} = 2\frac{g}{f_\pi}(P_a^\dagger P_{b\,\mu}^* + P_{a\,\mu}^{*\,\dagger} P_b)\partial^\mu \hat{\pi}_{ab}\,, \tag{1}$$

$$\mathcal{L}_{\pi P^* P^*} = 2i\frac{g}{f_\pi}\epsilon^{\alpha\beta\mu\nu}v_\alpha P_{a\,\beta}^{*\,\dagger} P_{b\,\mu}^* \partial_\nu \hat{\pi}_{ab}\,, \tag{2}$$

where $f_\pi = 135$ MeV is the pion decay constant. The coupling constant $|g| = 0.59$ is determined with reference to the observed decay width $\Gamma = 96$ keV for $D^* \to D\pi$, assuming that the charm quark is sufficiently heavy. And the interaction Lagrangians of vPP, vPP^* and vP^*P^* ($v = \rho,\ \omega$) are given by

$$\mathcal{L}_{vPP} = -\sqrt{2}\beta g_V P_b P_a^\dagger v \cdot \hat{\rho}_{ba}\,, \tag{3}$$

$$\mathcal{L}_{vPP^*} = -2\sqrt{2}\lambda g_V v_\mu \epsilon^{\mu\nu\alpha\beta}\left(P_a^\dagger P_{b\,\beta}^* - P_{a\,\beta}^{*\,\dagger} P_b\right)\partial_\nu(\hat{\rho}_\alpha)_{ba}\,, \tag{4}$$

$$\begin{aligned}\mathcal{L}_{vP^*P^*} = {}& \sqrt{2}\beta g_V P_b^* P_a^{*\dagger} v \cdot \hat{\rho}_{ba} \\ &+ i2\sqrt{2}\lambda g_V P_{a\,\mu}^{*\,\dagger} P_{b\,\nu}^*(\partial^\mu(\hat{\rho}^\nu)_{ba} - \partial^\nu(\hat{\rho}^\mu)_{ba})\,, \end{aligned} \tag{5}$$

where $g_V = 5.8$ is the coupling constant for $\rho \to \pi\pi$ decay. The coupling constants are fixed as $\beta = 0.9$ and $\lambda = 0.56$ GeV, which are determined by the radiative decays of D^* meson and semileptonic decays of B meson with vector meson dominance by following Ref. [5]. Due to the G-parity, the signs of vertices for $v\overline{P}\overline{P}$, $v\overline{P}\overline{P}^*$ and $v\overline{P}^*\overline{P}^*$ are opposite to those of vPP, vPP^* and vP^*P^*, respectively, for $v = \omega$, while they are the same for $v = \rho$.

Nex, we classify all the possible quantum numbers $I^G(J^{PC})$ with isospin I, G-parity, total angular momentum J, parity P and charge conjugation C for the states which can be composed by a pair of $P^{(*)}$ and $\overline{P}^{(*)}$ mesons. The charge conjugation C is defined for $I = 0$ or $I_z = 0$ components for $I = 1$, and is related to the G-parity by $G = (-1)^I C$. In the present discussion, we restrict upper limit of the total angular momentum as $J \le 2$, because too higher angular momentum will be disfavored to form bound or resonant states. To derive a potential between P and P^*, The $P^{(*)}\overline{P}^{(*)}$ components in the wave functions for various J^{PC} are listed in Table 1. We use the notation $^{2S+1}L_J$ to denote the total spin S and relative angular momentum L of the two body states of $P^{(*)}$ and $\overline{P}^{(*)}$ mesons. The $J^{PC} = 0^{+-}$ state cannot be generated by a combination of $P^{(*)}$ and $\overline{P}^{(*)}$ mesons. For $I = 0$, there are many $B^{(*)}\overline{B}^{(*)}$ states whose quantum number J^{PC} are the same as those of the quarkonia as shown in the third row of $I = 0$. In the present study, however, we do not consider these states, because we have not yet included mixing terms between the quarkonia and the $P^{(*)}\overline{P}^{(*)}$ states. This problem will be left as future works. Therefore, for $I = 0$, we

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consider only the exotic quantum numbers $J^{PC} = 0^{--}$, 1^{-+} and 2^{+-}. The states of $I = 1$ are clearly not accessible by quarkonia. We investigate all possible J^{PC} states listed in Table 1.

We obtain the potentials with channel-couplings for each quantum number $I^G(J^{PC})$ in terms of the interaction Lagrangians. For each state, the Hamiltonian is given as a sum of the kinetic energy and the potential with channel-couplings in a form of a matrix as

$$H_{JPC} = K_{JPC} + \sum_{i=\pi,\rho,\omega} V_{JPC}^i. \tag{6}$$

Breaking of the heavy quark symmetry is taken into account by mass difference between P and P* mesons in the kinetic term. The explicit forms of the Hamiltonian for each $I^G(J^{PC})$ are presented in Ref. [6]. For example, the $J^{PC} = 1^{+-}$ state has four components, $\frac{1}{\sqrt{2}}\left(P\overline{P}^* - P^*\overline{P}\right)(^3S_1)$, $\frac{1}{\sqrt{2}}\left(P\overline{P}^* - P^*\overline{P}\right)(^3D_1)$, $P^*\overline{P}^*(^3S_1)$, $P^*\overline{P}^*(^3D_1)$ and hence it gives a potential in the form of 4×4 matrix.

3 Numerical results

To obtain the solutions of the $P^{(*)}\overline{P}^{(*)}$ states, we solve numerically the Schrödinger equations which are second-order differential equations with channel-couplings. As numerics, the renormalized Numerov method developed in Ref. [7] is adopted. The resonant states are found from the phase shift δ as a function of the scattering energy E. The resonance position E_r is defined by an inflection point of the phase shift $\delta(E)$ and the resonance width by $\Gamma_r = 2/(d\delta/dE)_{E=E_r}$. To check consistency of our method with others, we also use the complex scaling method (CSM) [8]. We obtain an agreement in results between the renormalized Nemerov method and the CSM.

In Table 2, we summarize the result of the obtained bound and resonant states, and their possible decay modes to quarkonium and light flavor meson. For decay modes, the ρ meson can be either real or virtual depending on the mass of the decaying particle, depending on the resonance energy which is either sufficient or not to emit the real state of ρ or ω meson. $\rho^*(\omega^*)$ indicates that it is a virtual state in radiative decays assuming the vector meson dominance. We show the mass spectrum of these states in Fig 1.

Let us see the states of isospin $I = 1$. Interestingly, having the present potential we find the twin states in the $I^G(J^{PC}) = 1^+(1^{+-})$ near the $B\overline{B}^*$ and $B^*\overline{B}^*$ thresholds; a bound state slightly below the $B\overline{B}^*$ threshold, and a resonant state slightly above the $B^*\overline{B}^*$ threshold. The binding energy is 8.5 MeV, and the resonance energy and decay width are 50.4 MeV and 15.1 MeV, respectively, from the $B\overline{B}^*$ threshold. The twin states are obtained when the $\pi\rho\omega$ potential is used. We interpret them as the $Z_b(10610)$ and $Z_b(10650)$ observed in the Belle experiment [1, 2]. It should be

Table 1: Various components of the $P^{(*)}\overline{P}^{(*)}$ states for several J^{PC} ($J \leq 2$). The exotic quantum numbers which cannot be assigned to charmonia or bottomonia $Q\overline{Q}$ are indicated by $\checkmark$. The 0^{+-} state cannot be neither bottomonium nor $P^{(*)}\overline{P}^{(*)}$ states. Examples of bottomonia are shown in non-exotic quantum numbers.

J^{PC}	components	exoticness	
		$I = 0$	$I = 1$
0^{+-}	——	$\checkmark$	$\checkmark$
0^{++}	$P\overline{P}(^1S_0),\ P^*\overline{P}^*(^1S_0),\ P^*\overline{P}^*(^5D_0)$	χ_{b0}	$\checkmark$
0^{--}	$\frac{1}{\sqrt{2}}\left(P\overline{P}^* + P^*\overline{P}\right)(^3P_0)$	$\checkmark$	$\checkmark$
0^{-+}	$\frac{1}{\sqrt{2}}\left(P\overline{P}^* - P^*\overline{P}\right)(^3P_0),\ P^*\overline{P}^*(^3P_0)$	η_b	$\checkmark$
1^{+-}	$\frac{1}{\sqrt{2}}\left(P\overline{P}^* - P^*\overline{P}\right)(^3S_1),\ \frac{1}{\sqrt{2}}\left(P\overline{P}^* - P^*\overline{P}\right)(^3D_1),\ P^*\overline{P}^*(^3S_1),\ P^*\overline{P}^*(^3D_1)$	h_b	$\checkmark$
1^{++}	$\frac{1}{\sqrt{2}}\left(P\overline{P}^* + P^*\overline{P}\right)(^3S_1),\ \frac{1}{\sqrt{2}}\left(P\overline{P}^* + P^*\overline{P}\right)(^3D_1),\ P^*\overline{P}^*(^5D_1)$	χ_{b1}	$\checkmark$
1^{--}	$P\overline{P}(^1P_1),\ \frac{1}{\sqrt{2}}\left(P\overline{P}^* + P^*\overline{P}\right)(^3P_1),\ P^*\overline{P}^*(^1P_1),\ P^*\overline{P}^*(^5P_1),\ P^*\overline{P}^*(^5F_1)$	Υ	$\checkmark$
1^{-+}	$\frac{1}{\sqrt{2}}\left(P\overline{P}^* - P^*\overline{P}\right)(^3P_1),\ P^*\overline{P}^*(^3P_1)$	$\checkmark$	$\checkmark$
2^{+-}	$\frac{1}{\sqrt{2}}\left(P\overline{P}^* - P^*\overline{P}\right)(^3D_2),\ P^*\overline{P}^*(^3D_2)$	$\checkmark$	$\checkmark$
2^{++}	$P\overline{P}(^1D_2),\ \frac{1}{\sqrt{2}}\left(P\overline{P}^* + P^*\overline{P}\right)(^3D_2),\ P^*\overline{P}^*(^1D_2),\ P^*\overline{P}^*(^5S_2),\ P^*\overline{P}^*(^5D_2),\ P^*\overline{P}^*(^5G_2)$	χ_{b2}	$\checkmark$
2^{-+}	$\frac{1}{\sqrt{2}}\left(P\overline{P}^* - P^*\overline{P}\right)(^3P_2),\ \frac{1}{\sqrt{2}}\left(P\overline{P}^* - P^*\overline{P}\right)(^3F_2),\ P^*\overline{P}^*(^3P_2),\ P^*\overline{P}^*(^3F_2)$	η_{b2}	$\checkmark$
2^{--}	$\frac{1}{\sqrt{2}}\left(P\overline{P}^* + P^*\overline{P}\right)(^3P_2),\ \frac{1}{\sqrt{2}}\left(P\overline{P}^* + P^*\overline{P}\right)(^3F_2),\ P^*\overline{P}^*(^5P_2),\ P^*\overline{P}^*(^5F_2)$	ψ_{b2}	$\checkmark$

emphasized that the interaction in the present study has been determined in the previous works without knowing the experimental data of Z_b's.

Several comments are in order. First, the bound state of lower energy has been obtained in the coupled channel method of $B\overline{B}^*$ and $B^*\overline{B}^*$ channels. In reality, however, they also couple to other lower channels such as πh_b, $\pi\Upsilon$ and so on as shown in Table 1. Once these decay channels are included, the bound state will be a resonant state with a finite width. A qualitative discussion will be given in Section 5. Second, when the π exchange potential is used, only the lower bound state is obtained but the resonant state is not. However, we have verified that a small change in the π exchange potential generates, as well as the bound state, the corresponding resonant state also. Therefore, the pion dominance is working for the $B\overline{B}^*$ and $B^*\overline{B}^*$ systems. Third, it would provide a direct evidence of these states to be $B\overline{B}^*$ and $B^*\overline{B}^*$ molecules if the $B\overline{B}^*$ and $B^*\overline{B}^*$ decays are observed in experiments. Whether the energies are below or above the thresholds is also checked by the observation of these decays.

In other channels, we further predict the $B^{(*)}\overline{B}^{(*)}$ bound and resonant states. The $I^G(J^{PC}) = 1^-(0^{++})$ state is a bound state with binding energy 6.5 MeV from the $B\overline{B}$ threshold for the π exchange potential, while no structure for the $\pi\rho\omega$ potential. The existence of this state depends on the details of the potential, while the states in the other quantum numbers are rather robust. Let us see the results for the latter states from the $\pi\rho\omega$ potentials. For $1^+(0^{--})$ and $1^-(1^{++})$, we find bound states with binding energy 9.8 MeV and 1.9 MeV from the $B\overline{B}^*$ threshold, respectively. These bound states appear also for the π exchange potential, though the binding energy of the $1^-(1^{++})$ state becomes larger. The $1^-(2^{++})$ state is a resonant state with the resonance energy 62.7 MeV and the decay width 8.4 MeV. The $1^+(1^{--})$ states are twin resonances with the resonance energy 7.1 MeV and the decay width 37.4 MeV for the first resonance, and the resonance energy 58.6 MeV and the decay width 27.7 MeV for the second. The resonance energies are measured from the $B\overline{B}$ threshold. The $1^+(2^{--})$ states also form twin resonances with the resonance energy 2.0 MeV and the decay width 3.9 MeV for the first resonance and the resonance energy 44.1 MeV and the decay width 2.8 MeV for the second, where the resonance energies have are measured from the $B\overline{B}^*$ threshold.

Next we discuss the result for the states of isospin $I = 0$. In general, the interaction in these states are either repulsive or only weakly attractive as compared to the cases of $I = 1$. The fact that there are less channel-couplings explains less attraction partly. Because of this, we find only one resonant state with $I^G(J^{PC}) = 0^+(1^{-+})$, as shown in Fig 1 and in Table 3. The $0^+(1^{-+})$ state is a resonant state with the resonance energy 17.8 MeV and the decay width 30.1 MeV for the $\pi\rho\omega$ potential.

In the present study, all the states appear in the threshold regions and therefore are all weakly bound or resonant states. The present results are consequences of unique features of the bottom quark sector; the large reduced mass of the $B^{(*)}\overline{B}^{(*)}$

systems and the strong tensor force induced by the mixing of B and B* with small mass splitting. In fact, in the charm sector, our model does not predict any bound or resonant states in the region where we research numerically. Because the reduced mass is smaller and the mass splitting between D and D* is larger.

Table 2: Various properties of the B$^{(*)}\overline{\text{B}}^{(*)}$ bound and resonant states with possible $I^G(J^{PC})$ in $I = 1$. The energies E can be either pure real for bound states or complex for resonances. The real parts are measured from the thresholds as indicated in the second column. The imaginary parts are half of the decay widths of the resonances, $\Gamma/2$. In the last two columns, decay channels of a quarkonium and a light flavor meson are indicated. Asterisk of ρ^* indicates that the decay occures only with a virtual ρ while subsequently transit to a real photon via vector meson dominance.

$I^G(J^{PC})$	threshold	E [MeV]		decay channels	
		π-potential	$\pi\rho\,\omega$-potential	s-wave	p-wave
$1^+(0^{+-})$	—	—	—	—	$h_b + \pi$, $\chi_{b0,1,2}+\rho$
$1^-(0^{++})$	$B\overline{B}$	-6.5	no	$\eta_b+\pi$, $\Upsilon+\rho$	$h_b+\rho^*$, $\chi_{b1}+\pi$
$1^+(0^{--})$	$B\overline{B}^*$	-9.9	-9.8	$\chi_{b1}+\rho^*$	$\eta_b+\rho$, $\Upsilon+\pi$
$1^-(0^{-+})$	$B\overline{B}^*$	no	no	$h_b+\rho$, $\chi_{b0}+\pi$	$\Upsilon+\rho$
$1^+(1^{+-})$	$B\overline{B}^*$	-7.7	-8.5 $50.4-i15.1/2$	$\Upsilon+\pi$	$h_b+\pi$, $\chi_{b1}+\rho^*$
$1^-(1^{++})$	$B\overline{B}^*$	-16.7	-1.9	$\Upsilon+\rho$	$h_b+\rho^*$, $\chi_{b0,1}+\pi$
$1^+(1^{--})$	$B\overline{B}$	$7.0-i37.9/2$ $58.8-i30.0/2$	$7.1-i37.4/2$ $58.6-i27.7/2$	$h_b+\pi$, $\chi_{b0,1,2}+\rho^*$	$\eta_b+\rho$, $\Upsilon+\pi$
$1^-(1^{-+})$	$B\overline{B}^*$	no	no	$h_b+\rho$, $\chi_{b1}+\pi$	$\eta_b+\pi$, $\Upsilon+\rho$
$1^+(2^{+-})$	$B\overline{B}^*$	no	no	—	$h_b+\pi$, $\chi_{b0,1,2}+\rho$
$1^-(2^{++})$	$B\overline{B}$	$63.5-i8.3/2$	$62.7-i8.4/2$	$\Upsilon+\rho$	$h_b+\rho^*$, $\chi_{b1,2}+\pi$
$1^-(2^{-+})$	$B\overline{B}^*$	no	no	$h_b+\rho$	$\Upsilon+\rho$
$1^+(2^{--})$	$B\overline{B}^*$	$2.0-i4.1/2$ $44.2-i2.5/2$	$2.0-i3.9/2$ $44.1-i2.8/2$	$\chi_{b1}+\rho^*$	$\eta_b+\rho$, $\Upsilon+\pi$

4   Summary

In this paper, we have systematically studied the possibility of the the P$^{(*)}\overline{\text{P}}^{(*)}$ bound and resonant states having exotic quantum numbers $I^G(J^{PC})$. These states are consisted of at least four quarks, because their quantum numbers cannot be assigned by the quarkonium picture and hence they are genuinely exotic states. We have constructed the potential of the P$^{(*)}\overline{\text{P}}^{(*)}$ states using the effective Lagrangian respecting

Table 3: The $B^{(*)}\overline{B}^{(*)}$ bound and resonant states with exotic $I^G(J^{PC})$ in $I = 0$. (Same convention as Table II.)

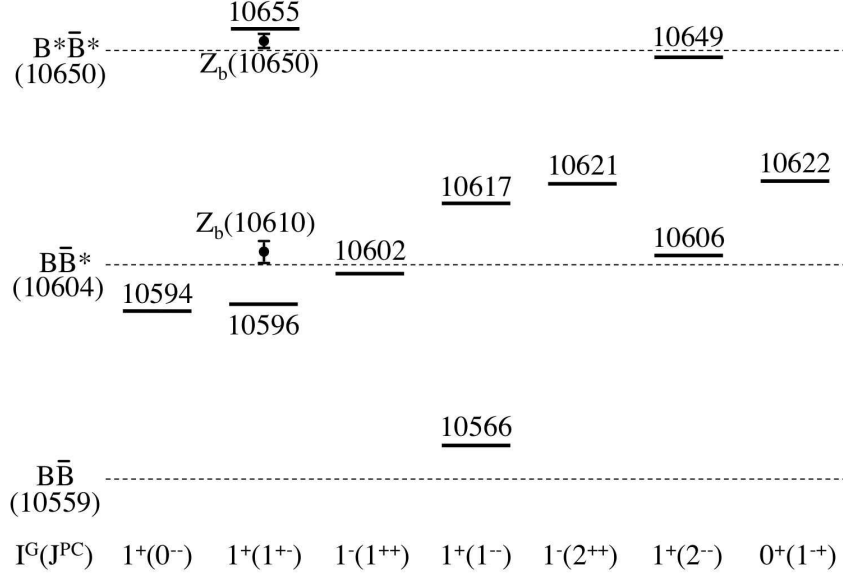| $I^G(J^{PC})$	threshold	E [MeV]		decay channels	
		π-potential	$\pi\rho\omega$-potential	s-wave	p-wave
$0^-(0^{--})$	$B\overline{B}^*$	no	no	$\chi_{b1}+\omega$	$\eta_b+\omega$, $\Upsilon+\eta$
$0^+(1^{-+})$	$B\overline{B}^*$	$28.6 - i91.6/2$	$17.8 - i30.1/2$	$h_b+\omega^*$, $\chi_{b1}+\eta$	$\eta_b+\eta$, $\Upsilon+\omega$
$0^-(2^{+-})$	$B\overline{B}^*$	no	no	—	$h_b+\eta$, $\chi_{b0,1,2}+\omega$

Figure 1: The $B^{(*)}\overline{B}^{(*)}$ bound and resonant states with exotic $I^G(J^{PC})$. The dots with error bars denote the position of the experimentaly observed Z_b's where $M(Z_b(10610)) = 10607.2$ MeV and $M(Z_b(10650)) = 10652.2$ MeV. Solid lines are for our predictions for the energies of the bound and resonant states when the $\pi\rho\omega$ potential is employed. Mass values are shown in units of MeV.

the heavy quark symmetry. The channel mixing due to the mass degeneracy of P and P* plays an important role to form the P$^{(*)}\overline{P}^{(*)}$ bound and/or resonant states. We have numerically solved the Schrödinger equation with the channel-couplings for the P$^{(*)}\overline{P}^{(*)}$ states with $I^G(J^{PC})$ for $J \leq 2$.

As a result, in $I = 1$, we have found that the $I^G(J^{PC}) = 1^+(1^{+-})$ states have a bound state with binding energy 8.5 MeV, and a resonant state with the resonance energy 50.4 MeV and the decay width 15.1 MeV. We have successfully reproduced the positions of $Z_b(10610)$ and $Z_b(10650)$ observed by Belle. Therefore, the twin resonances of Z_b's can be interpreted as the B$^{(*)}\overline{B}^{(*)}$ molecular type states. It should be noted that the B$\overline{B}^*$-B$^*\overline{B}$, B$\overline{B}^*$-B$^*\overline{B}^*$ and B$^*\overline{B}$-B$^*\overline{B}^*$ mixing effects are important, because many structures disappear without the mixing effects. We have obtained the other possible B$^{(*)}\overline{B}^{(*)}$ states in $I = 1$. We have found one bound state in each $1^+(0^{--})$ and $1^-(1^{++})$, one resonant state in $1^-(2^{++})$ and twin resonant states in each $1^+(1^{--})$ and $1^+(2^{--})$. It is remarkable that another two twin resonances can exist in addition to the Z_b's. We have also studied the B$^{(*)}\overline{B}^{(*)}$ states in $I = 0$ and found one resonant state in $0^+(1^{-+})$. We have checked the differences between the results from the π exchange potential and those from the $\pi\rho\omega$ potential, and found that the difference is small. Therefore, the one pion exchange potential dominates as the interaction in the B$^{(*)}\overline{B}^{(*)}$ bound and resonant states. We also study D$^{(*)}\overline{D}^{(*)}$ molecular states, but there are no bound/resonant states. Because the reduced mass is smaller and the mass splitting between D and D* is larger compared with bottom sector.

The $\Upsilon(5S)$ decay is a useful tool to search the B$^{(*)}\overline{B}^{(*)}$ states. $\Upsilon(5S)$ can decay to the B$^{(*)}\overline{B}^{(*)}$ states with $1^+(0^{--})$, $1^+(1^{--})$ and $1^+(2^{--})$ by a single pion emission in p-wave and the state with $0^+(1^{-+})$ by ω emission in p-wave. $\Upsilon(5S)$ can also decay to the B$^{(*)}\overline{B}^{(*)}$ states with $1^-(0^{++})$, $1^-(1^{++})$ and $1^-(2^{++})$ by radiative decays. In the future, various exotic states would be observed around the thresholds from $\Upsilon(5S)$ decays in accelerator facilities such as Belle and also would be searched in the relativistic heavy ion collisions in RHIC and LHC [9, 10]. If these states are fit in our predictions, they will be good candidates of the B$^{(*)}\overline{B}^{(*)}$ molecular states.

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